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EXPERIMENTAL EFFECTS OF PRESSURE, SUBCOOLING, AND DIAMETER ON THIN WIRE FILM BOILING

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TECHNICAL PAPER No. J-3 to be presented at
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ABSTRACT

Experimental data and high speed movies were taken for film boiling of liquid nitrogen on thin horizontal wires of 0.040 mm and 0.250 mm diameter. The data were taken over a range of pressures from atmospheric to critical, and fluid bulk temperatures from saturated to 45° K subcooled.

The saturated data followed existing analytic trends over the complete pressure and diameter range. The subcooled data exhibited a modest increase in heat transfer coefficient not exceeding 25% over the entire range.

The visual data examined the effect of pressure, subcooling and diameter on flow patterns and found the transition from axial to circumferential flow to be sensitive to all three parameters.

NOMENCLATURE

a	acceleration of gravity
C_v	vapor specific heat at constant volume
D_o	diameter of wire
g_c	conversion factor in Newton's law of motion
H*	modified latent heat of vaporization $H^* = H_{fg}\left(1 + 0.34\, C_v(T_w - T_s)/H_{fg}\right)^2$
H_{fg}	latent heat of vaporization
h	heat transfer coefficient
h*	dimensionless heat transfer coefficient defined by eq. (2)

k	vapor thermal conducitivity
l	characteristic length given by eq. (3)
P	system pressure
P_c	critical pressure (33.5 atm)
q	heat flux
T_B	liquid bulk temperature
T_s	liquid saturation temperature
T_w	wire temperature
ΔT_{sub}	subcooling (T_s - T_B)
λ	cell wavelength, see fig. 4
μ	absolute vapor viscosity
ρ	vapor density
ρ_L	liquid density
σ	surface tension

INTRODUCTION

Because of its low temperature a cryogenic fluid can film boil by simply bringing it in contact with an ambient or room temperature surface. As a result, film boiling is an important aspect of cryogenic heat transfer. It is also important in conventional boilers, in quenching and in similar applications.

The field of film boiling has been examined extensively both analytically and experimentally. Even if we confine ourselves to horizontal cylinders, as we will, a great deal of information is already available. Nevertheless, some important parameters remain to be explored and the present study proposes to examine some of them. The majority of experimental work has been confined to saturated atmospheric pressure boiling off large cylinders. There is still room for study of pressure, subcooling and wire diameter effects, especially on thin wires.

Thin is a relative term and, as will be discussed later, the degree of ''thinness'' is a function of fluid properties. However, to place this term in perspective we can say that horizontal cylinders on the order of 0.5 mm (0.020 in.) diameter or less will generally fall into the ''thin'' class

The earliest work relative to the present study is that of Bromley (ref. 1). Bromley derived analytically a correlation for film boiling based on circumferential flow around a large cylinder which introduced the property grouping expressed in equation (1)

$$h = \text{Const.}\left[\frac{k^3 H^* a(\rho_L - \rho)\rho}{\mu(T_w - T_s)D_o}\right]^{1/4} \tag{1}$$

Bromley's equation worked well for the existing data for cylinders of 6.35 to 19.1 mm diameter.

Banchero (ref. 2), using oxygen, examined the effect of pressure and wire diameter on film boiling. He reported that small diameter wires tended to deviate from the Bromley equation.

In 1962 Breen and Westwater (ref. 3) introduced new data and gathered the existing data of references (1, 2, 4, 5 and 6) and offered a correlation based on the property grouping of Bromley and the concept of the most dangerous wavelength. The correlation showed a strong influence of the ratio of wavelength to diameter on heat transfer coefficient for small diameter wires.

In 1967 Baumeister and Hamill (refs. 7 and 8) proposed an analytic model for thin wires based on axial flow of vapor along the wire into the vapor domes as opposed to circumferential flow as found in large diameter cylinders (c.f. Bromley). The analysis yielded the same property grouping Bromley derived as well as the wavelength property grouping. It correlated all the data, and agreed excellent with the Breen and Westwater empiricism. The resulting equation was

$$h^* = \frac{h}{\left[\frac{k^3 H^* a(\rho_L - \rho)\rho}{\mu(T_w - T_s)l}\right]^{1/4}} = 0.373\left[1 + \frac{9l}{\sqrt{6}\,D_o} + \frac{8}{3\sqrt{6}}\left(\frac{l}{D_o}\right)^3\right]^{1/4} \qquad (2)$$

where

$$l = \left[\frac{g_c \sigma}{a(\rho_L - \rho)}\right]^{1/2} = \frac{\lambda_{critical}}{2\pi} \qquad (3)$$

The theoretical point where Bromley's model (1) and the model of Baumeister and Hamill (refs. 7 and 8) begin to diverge is approximately $l/D_o \geq 1.5$. Thus, analytically, we should expect circumferential flow around large diameter cylinders for $l/D_o < 1.5$ and axial flow along small diameter, "thin," wires for $l/D_o > 1.5$.

Several experiments (refs. 9 to 13) have been conducted on large diameter cylinders in recent years. They examined pressure, acceleration and different fluids and tended to confirm the validity of Bromley's work. Although Banchero did work with small wires, at elevated pressures he was in the l/D_o range of large cylinders.

The most pertinent references to the present work are references 14 and 15. Grigull and Abadzic (ref. 14) film boiled saturated CO_2 on a 0.100 mm wire at pressures from $P/P_c = 0.7$ to the critical point. They coupled high speed photographs with data and observed that the flow field changed drastically at $P/P_c \approx 0.99$ although no heat transfer change was observed. Nishikawa and Miyabe (ref. 15) displayed similar results.

The present study is a combined visual and data experiment with film boiling liquid nitrogen for cylinder diameters of 0.040 mm and 0.250 mm and pressure ratios $0.03 < P/P_c < 0.99$. Saturated and subcooled data was taken over all pressures with subcooling as high as high as 45° K for the higher pressures. Preliminary results of saturated boiling on the 0.250 mm wire were reported at the previous Cryogenic Engineering Conference (ref. 16). The results showed the data followed the Baumeister-Hamill model trend over the pressure range $0.03 < P/P_c < 0.99$. They confirmed a change in flow field with pressure but considered the results consistent with the Bromley and Baumeister-Hamill demarcation. A more complete story is presented herein. The present study includes a large body of data and a movie supplement which will be documented in an NASA TN (ref. 17).

DESCRIPTION OF EXPERIMENT

The experiment was conducted in a double walled pressure vessel as shown in figure 1. The inner vessel was a 16.0 cm diameter by 32.0 cm high pressure vessel capable of operating up to 38 atm (P_c of nitrogen is 33.5 atm). The outer vessel was a vacuum insulating jacket. The assembly was equipped with quartz windows front and back for viewing. The system was pressurized on top with nitrogen gas. A 100 watt calrod heater was used to heat the pool to the desired bulk temperature following pressurization.

The test wires were mounted horizontally under spring tension to an assembly which was in turn mounted to an access door as shown in figure 2. All the instruments and lead wires were also mounted to the door. Two 0.250 mm diameter platinum wires 5.44 and 5.48 cm long and one 0.040 mm diameter wire 4.58 cm long were used as test heaters. Two pins 0.800 mm diameter were inserted in the mounting assembly below the wire at distances apart of 5.43 mm for the 0.250 mm wire and 5.60 mm for the 0.040 mm wire. These provide a dimensional reference for the visual observations.

Pressure was measured with a bourdon tube gage accurate to 0.1 percent of full scale. Fluid temperature was measured with a platinum resistance thermometer rated accurate to within 0.1° K. The resistance of the platinum heater wire was calibrated and found to follow that of standard platinum. The average wire temperature was determined by measuring voltage drop across the wire and current through the wire. Heat was generated using a d.c. power supply with rms ripple of less than 0.05 percent of test voltage. A precision digital voltmeter was used for voltage measurements. Current was measured using the same instrument and a calibrated shunt. All measurements were backed up by redundant instruments. The system had a tendency to drift slightly while acquiring data. This coupled with reproducibility results limit claims on data accuracy to the following values: pressure, ±1.0%; fluid temperature, $\pm 0.2^{\circ}$ K; wire temperature, ±5%; and heat flux, ±5%.

The photographs were taken with a 16 mm high speed movie camera operating at 400 frames per second. Lighting was provided from the back by a 1000 watt lamp diffused through a frosted glass for better shadowgraph.

RESULTS

Data were taken in the manner described above for film boiling of liquid nitrogen on 0.250 mm and 0.040 mm diameter horizontal platinum wires over the following range of conditions.

$$0.03 \leq P/P_c \leq 0.99$$

$$78 \leq T_B \leq 126^{\circ}\ \mathrm{K}$$

$$250 < T_w < 900^{\circ}\ \mathrm{K}$$

$$0 \leq \Delta T_{sub} \leq 45^{\circ}\ \mathrm{K}$$

$$8 \leq q \leq 70\ \mathrm{watts/cm^2}$$

Of course, all combinations were not possible; for instance, the high subcooling can be achieved only at high pressure. More data were

taken on the larger wire. The raw data, along with the movie film supplement, are documented in reference 17.

Saturated film Boiling

The main purpose of this experiment was to examine film boiling on thin wires (with simultaneous data and visual record) over a wide range of parameters to test the range of the Baumeister-Hamill analysis (refs. 7 and 8). The first phase was to examine pressure and wire diameter effect on saturated film boiling. All points with $|\Delta T_{sub}| < 0.5^{\circ} K$ were designated saturated.

The raw data results are presented in figure 3 with heat transfer coefficient plotted against critical pressure ratio for the two wire diameters. The most striking result is the diameter effect which shows that a 6 fold decrease in diameter yields a 2 to 3 times increase in heat transfer coefficient depending on pressure. The second result is a maximum in heat transfer coefficients as function of pressure occurs around P/P_c of 0.6 to 0.7.

Figure 3 can also be examined for data scatter. In the course of the experiment the first 0.250 mm wire broke. It was replaced. Subsequently, the second wire was removed to take the 0.040 mm data. Finally the second 0.250 mm wire was reinstalled for more data. In figure 3 saturated data are shown for all 3 cases. Thus we can examine the effects of scatter within an individual run, of deviation between two different wires, and of errors introduced by disconnecting and connecting instruments. The result is that, if all the data are to be used for some composite reason they have to be accepted with a reproducibility of about ±8%. If individual runs are used the scatter decreases. Additional remarks on this will be made later. It should be observed that each of the individual runs exhibits the same trends.

In figure 4 one can see how this data squares with the existing theory of film boiling on horizontal wires. The data in figure 4 cover all of the heat flux range, not just 35 watts/cm^2. The data and theoretical trends are in reasonable agreement and the region of overlap is encouraging. With only the larger wire data available Baumeister

and Simoneau (ref. 16) suggested the constant in equation (2) could be increased about 25%. At present it is probably best to leave that to the discretion of the individual reader.

Recalling that the circumferential flow model (1) deviates from the axial flow model (refs. 7 and 8) at $l/D_o \geq 1.5$ one would expect a transition from one flow pattern to the other in this region. Figure 5 is a set of photographs of the flow patterns for the entire pressure range (and consequently l/D_o range) arranged along the correlation curve. At $P/P_c = 0.44$ the flow is clearly axial and at $P/P_c = 0.85$ is circumferential. At $P/P_c = 0.74$ ($l/D_o = 1.56$) it may be in transition.

Is this merely a fortuitous coincidence? This question can be answered by examining two wire diameters. The parameter l/D_o decreases as both pressure and diameter increase. Thus if the model formulation is correct, flow transition should occur at higher pressure for the smaller diameter wire. In figure 6 the photographs of the flow patterns are displayed side by side at each pressure level for the two wires. It can be clearly seen that as a first order condition it is true that transition occurs at higher pressure for small diameter wires. However, for the 0.040 mm wire it would appear that transition occurs between $P/P_c = 0.94$ and $P/P_c = 0.97$ at $l/D_o \approx 4$. Since at $l/D_o = 4$ the larger wire is definitely in axial flow the use of l/D_o to mark transition is probably an oversimplification. However as a first order remark it is probably safe to say flow-transition is likely to occur at some specific value in a band $1 < l/D_o < 5$. The data conditions of figures 5 and 6 correspond to figure 3.

Transition in flow for the small (0.040 mm) wire occurred at very near critical conditions. Consequently it would be easy to interpret the strange flow patterns associated with circumferential flow as some near critical phenomena. Since the same patterns occur at $P/P_c \approx 0.8$ for the larger wire it is not likely that these patterns are near critical phenomena per se. Grigull and Abadzic (ref. 14) obtained similar patterns on a 0.100 mm wire with CO_2 at $P/P_c > 0.9$ and quite reasonably associated this with the critical point. The present evidence suggests a reinterpretation of that data.

Subcooled Film Boiling

The remaining parameter investigated was subcooling. Figure 7 is a plot of heat transfer coefficient against pressure with subcooling as a parameter. The heat transfer coefficient is based on saturation temperature (i.e., $h = q/(T_w - T_s)$). The effect of subcooling appears to be about a 5% increase in heat transfer coefficient for about every 10 degrees Kelvin subcooling with a total of less than 25% increase over the entire range of the experiment. The trend with pressure seems to be consistent with the saturated data.

The authors did not anticipate such a modest subcooling effect and it caused some experimental problems. Recall the overall data scatter runs about ±8%. This would pretty well obliterate any subcooling trends. Thus the data of figure 7 were taken on a single day with no intermediate adjustments on the equipment. Since the single run scatter is considerably less than the overall, the trends of figure 7 are considered genuine.

The data follow the correlation trend of figure 4 though slightly higher. If we were to plot the data in the manner of figure 4 the increase would be buried in the scatter and the implication would be that equation (2) is as good as it is for the saturated data. This is not true since there is some subcooling effect and thus the data are not displayed in this manner. The fact that they follow the trend, however, indicates that the currently used property grouping would be basic to a subcooling correlation.

The final question is the effect of subcooling on flow pattern. Figure 8 displays flow field photographs for 3 pressures over a range of subcoolings using the large wire. In the first column the saturated flow field at $P/P_c = 0.54$ is axial. Increasing subcooling merely affects bubble size. However at $P/P_c = 0.84$ the saturated flow field is circumferential. An increase in subcooling changes the pattern to axial. Finally, at $P/P_c = 0.94$ the flow is circumferential and remains so. Since l/D_o is a saturation parameter these pictures again point out that l/D_o is an oversimplification in designating flow transition and is only a first order concept.

SUMMARY

Film boiling liquid nitrogen data and high speed movies were taken in a pool on thin horizontal wires of 0.250 mm and 0.040 mm diameters. The data were taken over a range of pressures from atmospheric to critical, and fluid bulk temperatures from saturated to 45° K subcooled. The primary results were:

1. Saturated film boiling nitrogen heat transfer coefficients increase as wire diameter decreases and exhibit a maximum with pressure around $P/P_c = 0.7$.

2. The Baumeister-Hamill analysis (refs. 7 and 8), equation (2), correlates the data trends adequately but is somewhat low in magnitude.

3. Visual evidence supports the use of a circumferential flow model for large diameter wires and an axial flow model for small diameters. To a first approximation the transition occurs around $1 < l/D_o < 5$. The pictures suggest l/D_o is an oversimplification in discussing flow transition.

4. For film boiling subcooled nitrogen on thin wires an increase of about 10° K in subcooling produces an increase of about 5% in heat transfer coefficient.

5. Visual evidence indicates that the transition from axial to circumferential flow is influenced by subcooling.

REFERENCES

1. Bromley, LeRoy A.: Heat Transfer in Stable Film Boiling. Chem. Eng. Progr., vol. 46, no. 5, May 1950, pp. 221-227.

2. Banchero, J. T.; Barker, G. E.; and Boll, R. H.: Stable Film Boiling of Liquid Oxygen Outside Single Horizontal Tubes and Wires. Chem. Eng. Progr. Symp. Ser., vol. 51, no. 17, 1955, pp. 21-31.

3. Breen, B. P.; and Westwater, J. W.: Effect of Diameter of Horizontal Tubes on Film Boiling Heat Transfer. Chem. Eng. Progr., vol. 58, no. 7, July 1962, pp. 67-72.

4. McAdams, W. H.; Addoms, J. N.; Rinaldo, P. M.; and Day, R. S.: Heat Transfer from Single Horizontal Wires to Boiling Water. Chem. Eng. Progr., vol. 44, no. 8, Aug. 1948, pp. 639-646.

5. Nukiyama, Shiro: Maximum and Minimum Values of Heat Transmitted from Metal to Boiling Water Under Atmospheric Pressure. J. Soc. Mech. Eng. Japan, vol. 37, no. 206, June 1934, pp. 367-374.

6. Frederking, T. H. K.: Film Boiling of Helium I and Other Liquefied Gases on Single Wires. AIChE J., vol. 5, no. 3, Sept. 1959, pp. 403-406.

7. Baumeister, Kenneth J.; and Hamill, Thomas D.: Laminar Flow Analysis of Film Boiling From a Horizontal Wire. NASA TN D-4035, 1967.

8. Baumeister, K. J.; and Hamill, T. D.: Film Boiling from a Thin Wire as an Optimal Boundary-Value Process. Paper 67-HT-62, ASME, Aug. 1967.

9. Pomerantz, M. L.: Film Boiling on a Horizontal Tube in Increased Gravity Fields. J. Heat Transfer, vol. 86, no. 2, May 1964, pp. 213-219.

10. Sciance, C. T.; Colver, C. P.; and Sliepcevich, C. M.: Pool Boiling of Methane Between Atmospheric Pressure and the Critical Pressure. Advances in Cryogenic Engineering. Vol. 12. K. D. Timmerhaus, ed., Plenum Press, 1967, pp. 395-408.

11. Sciance, C. T.; Colver, C. Phillip; and Sliepecevich, C. M.: Film Boiling Measurements and Correlation for Liquefied Hydrocarbon Bases. Chem. Eng. Progr. Symp. Ser., vol. 63, no. 77, 1967, pp. 115-119.

12. Brown, L. E.; and Colver, C. P.: Nucleate and Film Boiling Heat Transfer to Liquefied Natural Gas. Advances in Cryogenic Engineering. Vol. 13. K. D. Timmerhaus, ed., Plenum Press, 1968, pp. 647-654.

13. Capone, G. J.; and Park, E. L., Jr.: Estimation of Film Boiling Heat Transfer Coefficients for Cylindrical Heaters in Corresponding States Fluids. Presented at the 1969 Cryogenic Engineering Conference, Univ. California, Los Angeles, June 16-18, 1969.

14. Grigull, U.; and Abadzic, E.: Heat Transfer from a Wire in the Critical Region. Paper 8, Symposium on Heat Transfer and Fluid Dynamics of Near Critical Fluids, Inst. Mech. Eng., Bristol, England, Mar. 27-29, 1968.

15. Nishikawa, Kaneyasu; and Miyabe, Kiyoji: On the Boiling-Like Phenomena at Supercritical Pressures. Mem. Fac. Eng. Kyusha Univ., vol. 25, no. 1, 1965, pp. 1-25.

16. Baumesiter, K. J.; and Simoneau, R. J.: Saturated Film Boiling of Nitrogen from Atmospheric to the Critical Pressure. Advances in Cryogenic Engineering. Vol. 15. K. D. Timmerhaus, ed., 1970 (to be published).

17. Simoneau, R. J.; and Baumeister, K. J.: Photographic and Data Study of Pressure, Subcooling, and Diameter Effects on Film Boiling Nitrogen on Horizontal Thin Wires (With Film Supplement) Proposed NASA TN.

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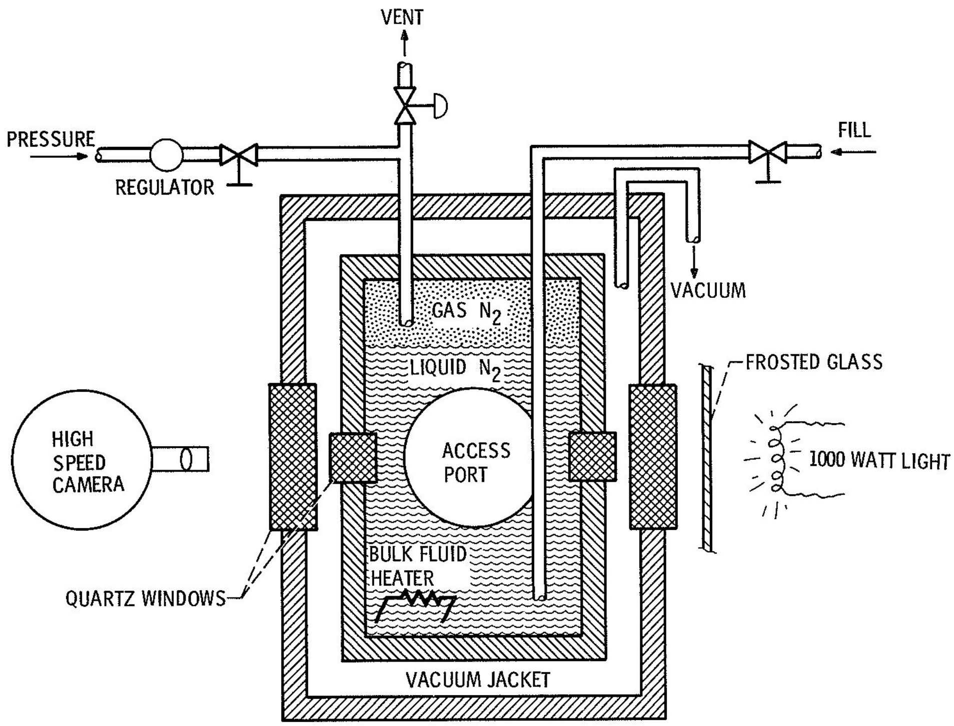

Figure 1. - Liquid nitrogen pool-schematic layout.

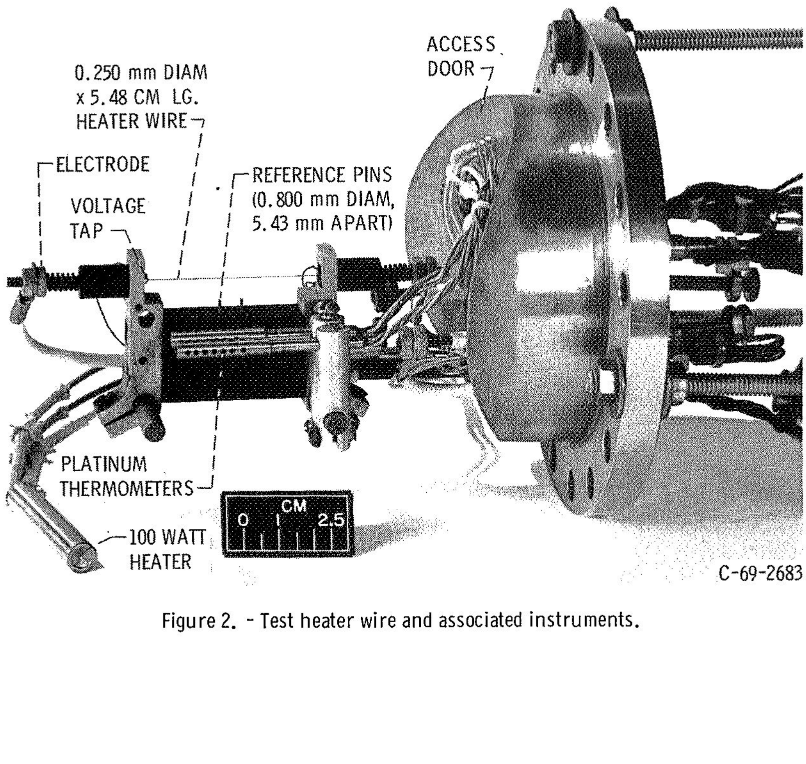

Figure 2. - Test heater wire and associated instruments.

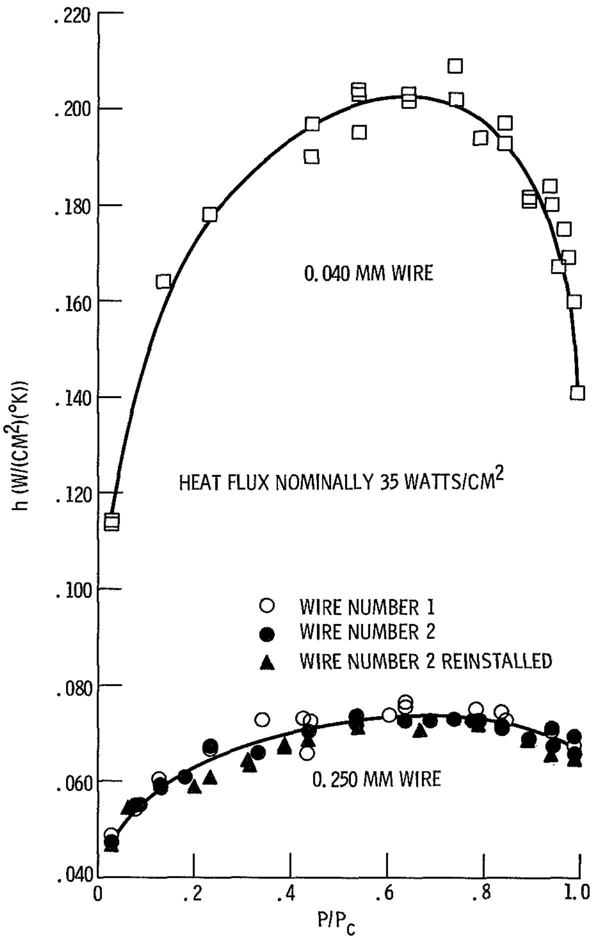

Figure 3. - Effect of diameter and pressure on saturated film boiling.

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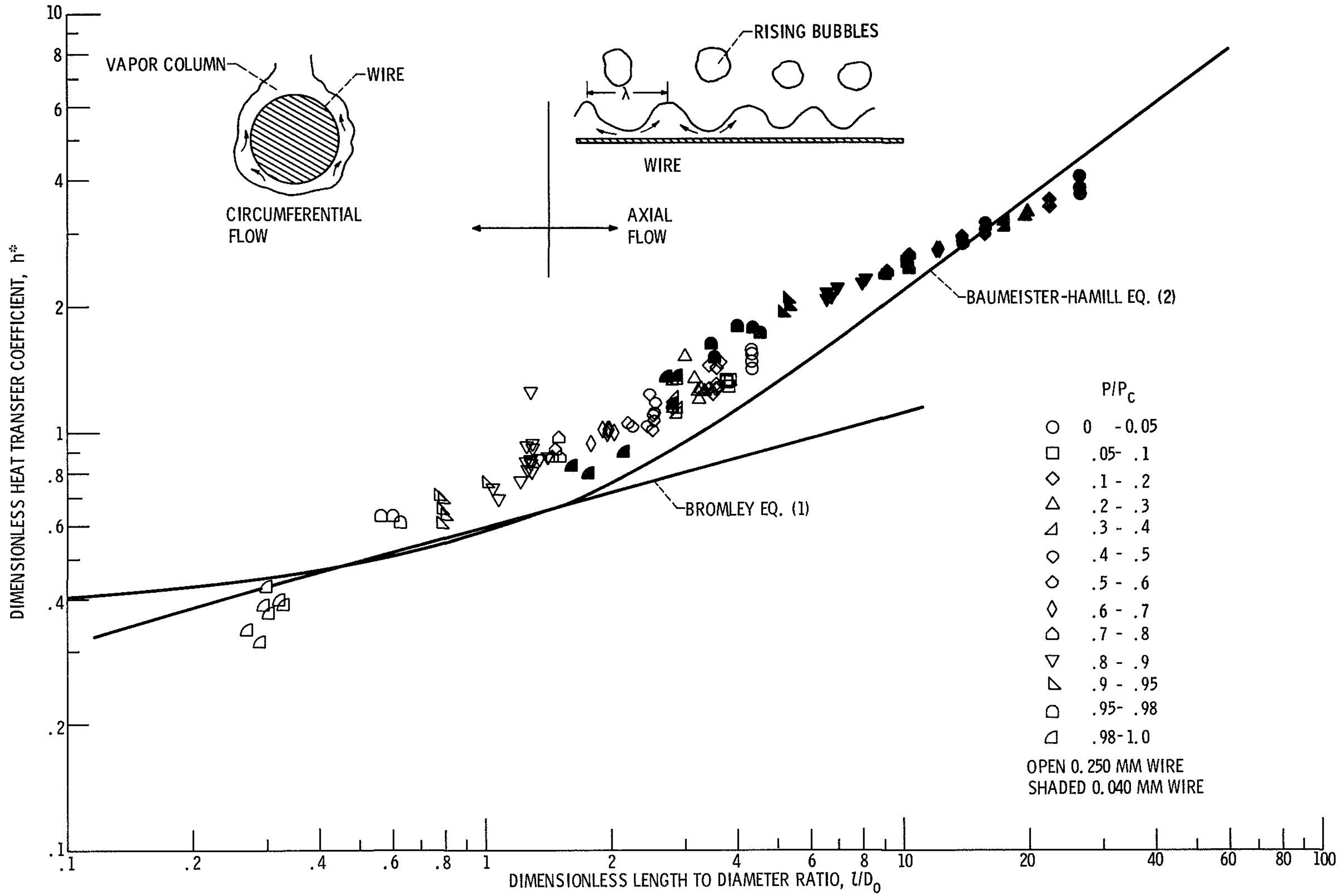

Figure 4. - Saturated film boiling heat transfer data of nitrogen from atmospheric to the critical pressure.

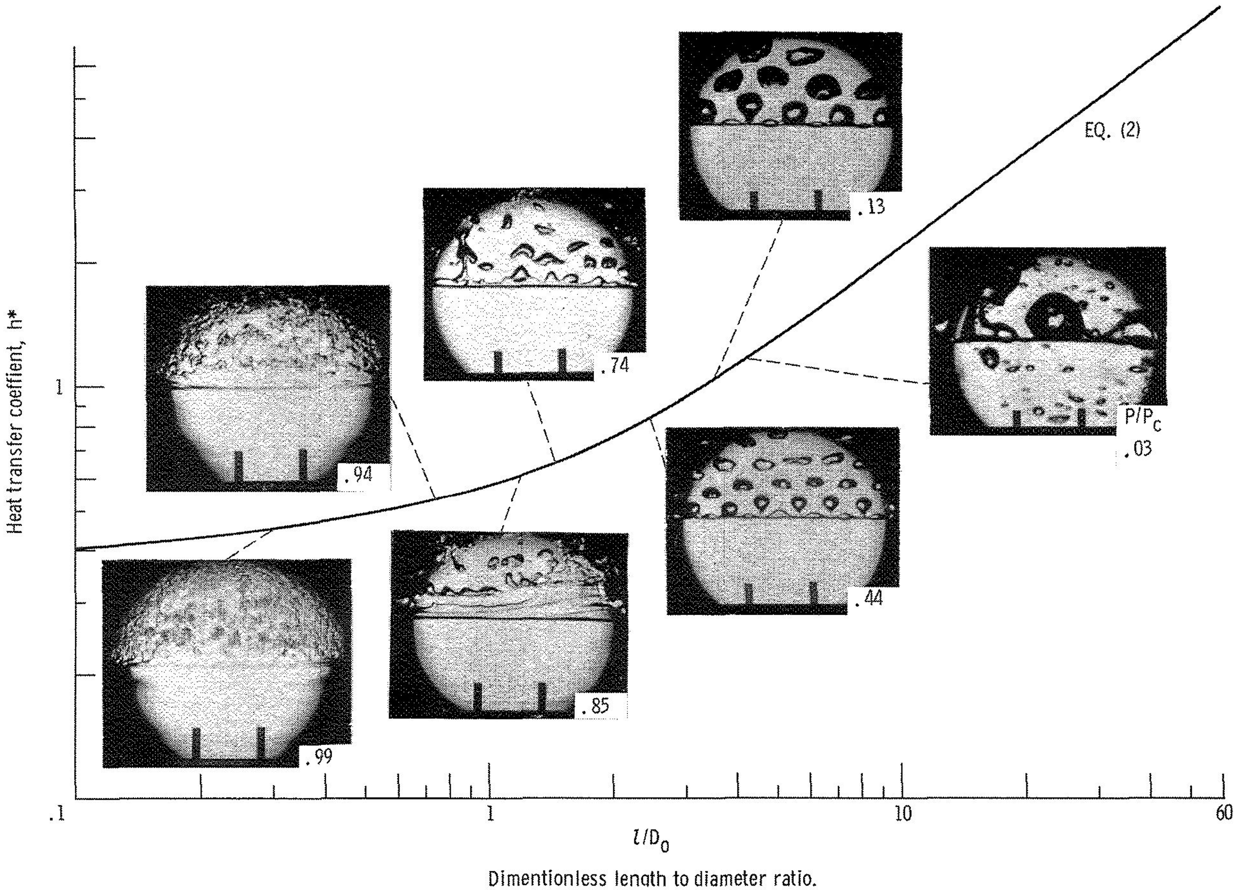

Figure 5. - Effect of pressure on flow patterns for saturated film boiling from a horizontal 0.250 mm wire. ($q \approx 35$ W/cm^2).

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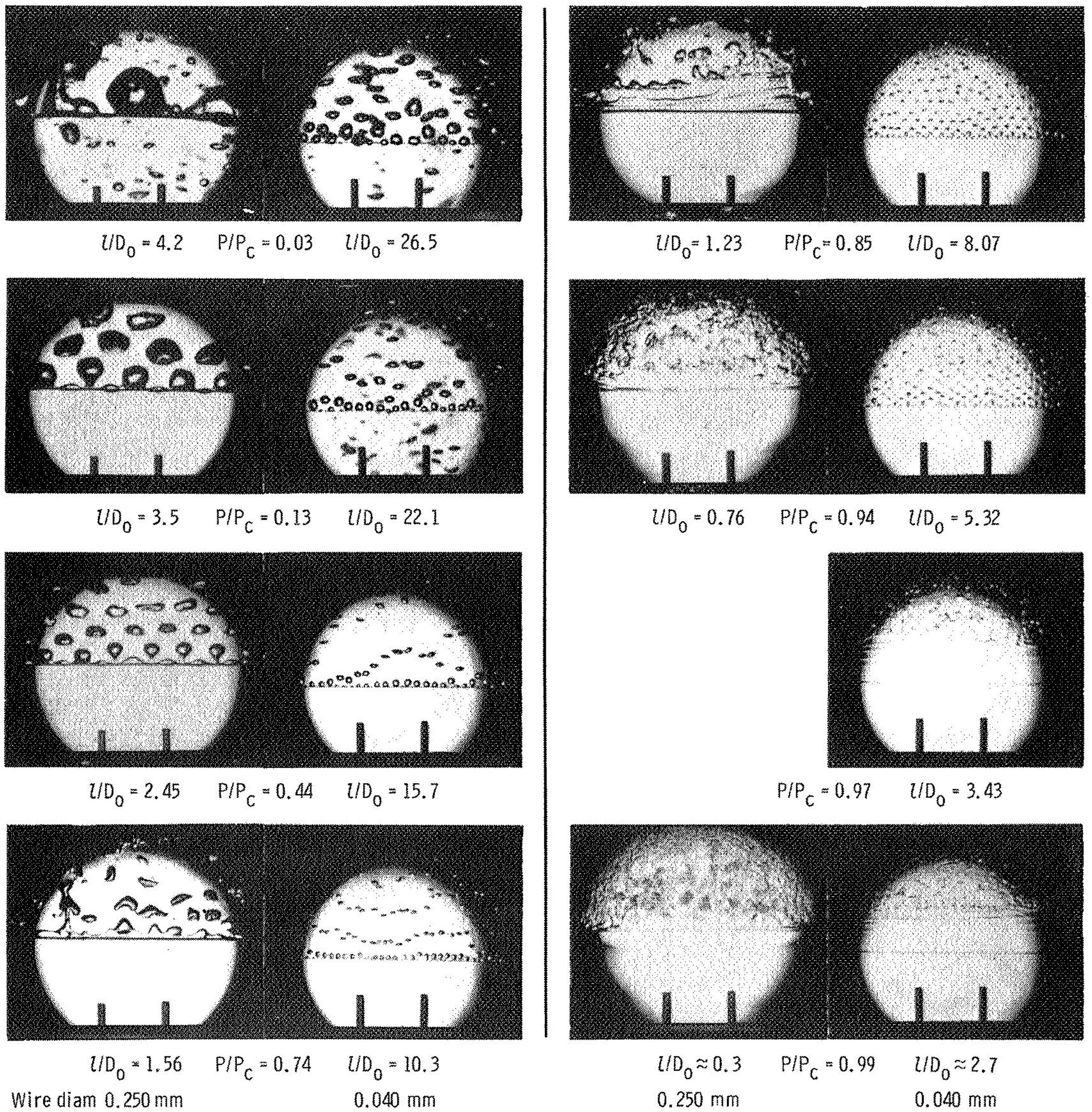

Figure 6. - Effect of diameter and pressure on the saturated liquid-vapor interface. ($q \approx 35\ W/cm^2$).

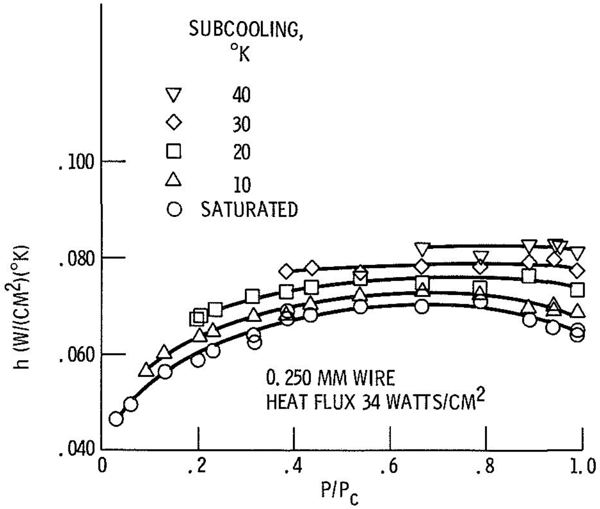

Figure 7. - Effect of subcooling and pressure on nitrogen film boiling heat transfer coefficient.

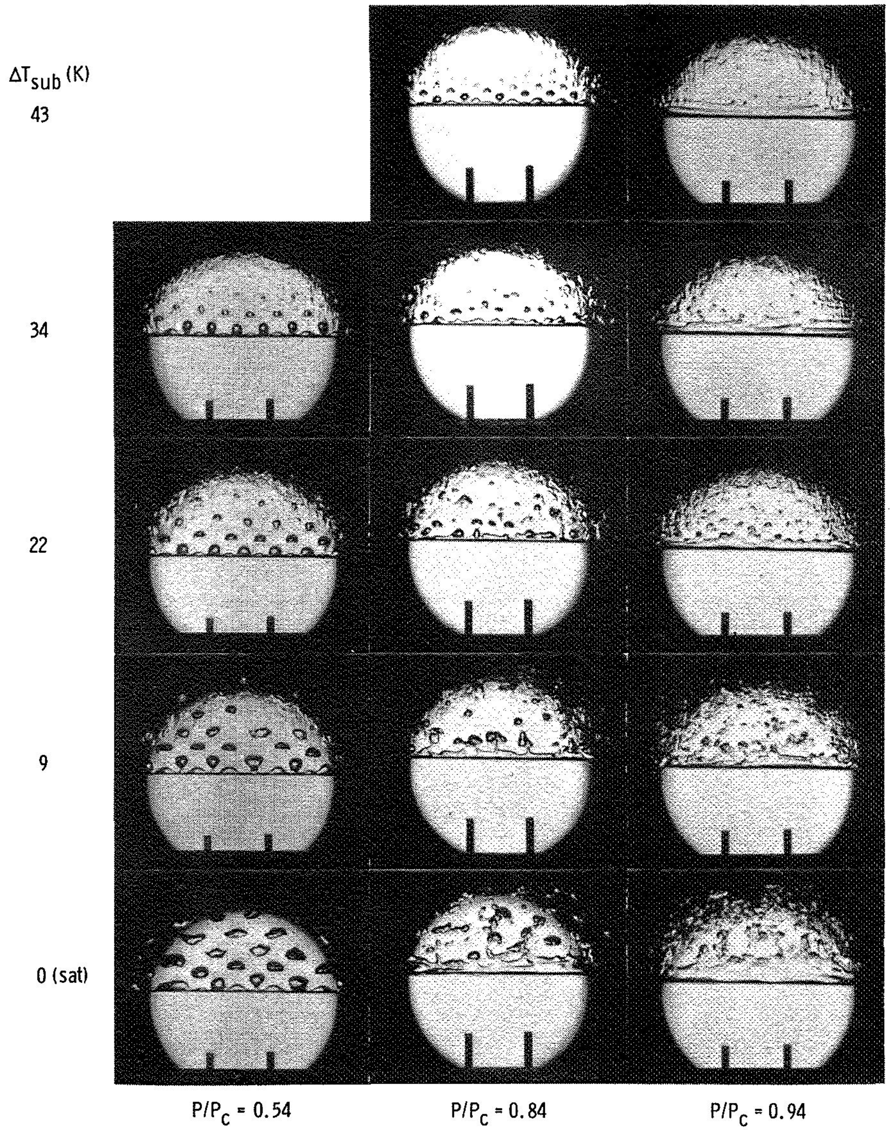

Figure 8. - Effect of pressure and subcooling on liquid vapor interface for 0.250 mm wire. ($q \approx 35$ W/cm^2).